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Relative solar and auroral contribution to the polar *F* region: Implications for National Space Weather Program

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[1] When plasma in the polar cap *F* region becomes highly structured, patches, irregularities, and scintillations of HF signals may be observed. The topic of this paper is not the mechanism for structuring or distributing the plasma but rather the source of the plasma. By understanding the plasma source we gain insight into the specification and forecasting of ionospheric structures and irregularities as required for space weather applications. The two major sources of polar cap *F* region plasma are the solar EUV radiation and the auroral precipitation. The region over which solar EUV production occurs is readily modeled. In contrast, the auroral precipitation is not subject to diurnal or seasonal dependences in the same predictable manner; the auroral precipitation can almost be viewed as stochastic within certain geomagnetic coordinate constraints. In this study we use a physical model to separate the effects of solar EUV and auroral precipitation. We find that the auroral contribution does provide a far-from-negligible "baseline" level of polar cap *F* region plasma, upon which is superimposed the UT and seasonally dependent TOI. This baseline level of ionization is very difficult to predict or forecast since it is determined by plasma flux tube histories through extended regions of the auroral oval over several hours. This result raises the need for more advanced auroral precipitation modeling in order to obtain improved space weather specification. The inclusion of soft auroral precipitation is especially important since it can be a significant source of *F* region plasma. *INDEX TERMS:* 2475 Ionosphere: Polar cap ionosphere; 2423 Ionosphere: Ionization mechanisms; 2479 Ionosphere: Solar radiation and cosmic ray effects; 2455 Ionosphere: Particle precipitation; *KEYWORDS:* auroral ionization, solar ionization, *F* region, polar cap, structure

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1. Introduction

[2] The polar regions of the ionosphere are known to undergo structuring over a wide range of scales. These structures range from the macro scale of hundreds to thousands of kilometers as polar holes and the tongue of ionization (TOI); through intermediate scales of tens to several hundred kilometers as patches and boundary layer blobs; to small scales of less than a few kilometers as irregularities. In the polar region the smallest scales are presumed to have originated through cascading processes from the largest scale structures. A review by *Tsunoda* [1988] contrasts the polar cap instability processes with those prevalent in auroral regions. Present-day research supports the Tsunoda summary of sources and instabilities. The empirical discovery and categorization of the plasma structures at high latitudes was pioneered by researchers at the Air Force Geophysical Laboratory at Hanscom Air Force Base in the early 1980s [*Buchau et al.*, 1983, 1985; *Weber et al.*, 1984, 1986]. These have been extensively summarized in the review by *Tsunoda* [1988].

[3] In the 1990s extensive model-observation collaboration was undertaken to identify the primary large scale structure sources and mechanisms. These studies were enabled by three international workshops held at Peaceful Valley, Colorado, in 1992, 1994, and 1997. The workshops were cosponsored by the NSF CEDAR High Latitude Plasma Structures (HLPS) working group and the International STEP Global Aspects of Plasma Structures (GAPS) working group. Many of the new results were published in special sections "Coupling, Energetics, and Dynamics of Atmospheric Regions" [*Radio Science*, *29*(1), 155–405,1994] "High-Latitude Plasma Structures" [*Radio Science*, *31*(3), 573–677, 1996], and "HLPS/GAPS Peaceful Valley III Workshop" [*Radio Science*, *33*(6), 1827–1937, 1998]. Some key findings of these workshops and collaborations were that the high density TOI/patch structures have a solar source, that subsequent plasma convection through the cusp into the polar cap is crucial, and that

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dynamic changes in convection are largely responsible for breaking up the TOI into patches. However, the dynamic processes are numerous, including IMF changes, flow channel events, polar cap expansion, and others. Reviews by *Rodger* [1998] and *Basu and Valladares* [1999] summarize these results. If solar production is in fact the key plasma source then models can predict both UT and seasonal dependences of the structures [*Bowline et al.*, 1996; *Sojka et al.*, 1993]. In the Northern Hemisphere observational evidence supports such predictions [*Basu et al.*, 1995; *Rodger and Graham*, 1996]; however, in the Southern Hemisphere this is not quite so clear [*Coley and Heelis*, 1998].

[4] To a large extent the modelers and observers all suffer from the common problem that each is often defining a TOI or a patch in ways different from the others. Even the issue of how big a patch is depends on technique and threshold sensitivity. The modeling community can readily identify a peak density from a two-dimensional snapshot of N_mF_2 and even a width at half-peak intensity. However, in some observations it is not evident that the absolute peak has been measured or that a parameter scales linearly with N_mF_2, i.e., optical emissions or scintillation intensity.

[5] This brief report revisits the question of the plasma source for the background in the polar cap as well as for structures within the background. Our purpose is to establish whether the background plasma can significantly contribute to, control, or mask plasma structures and instabilities. The method adopted to determine the relative importance of the two main plasma sources, solar EUV and auroral precipitation, somewhat follows the method used by *Fuller-Rowell et al.* [1991], i.e., separate simulations are created for different combinations of ionospheric drivers for the same geophysical and solar conditions. This study can also be viewed as a continuation of modeling efforts of the early 1990s following the suggestions of *Rodger et al.* [1994], who were interested in the role of auroral precipitation in the creation of plasma structures; specifically, that enhanced soft electron precipitation in the cusp might generate plasma structures. *Millward et al.* [1999] carried out detailed *F* region density calculations using the Sheffield High-Latitude Ionosphere (SHL) model to study the effect of soft precipitation in the cusp; their results quantify the dynamic range over which cusp precipitation can enhance the density of plasma flux tubes that cross the cusp. These constitute a subset of flux tubes of interest to this study. A comparison of *Millward et al.* [1999] and this study will be made in the discussion section. This comparison is particularly relevant since we use the standard *Hardy et al.* [1987] precipitation model, which does not have the very soft cusp precipitation fluxes.

2. Time-Dependent Ionospheric Model (TDIM)

[6] The TDIM ionospheric model was initially developed as a midlatitude, multi-ion (NO^+, O_2^+, N_2^+, and O^+) model by *Schunk and Walker* [1973]. The time-dependent ion continuity and momentum equations were solved as a function of altitude for a corotating plasma flux tube including diurnal variations and all relevant *E* and *F* region processes. This model was extended to include high-latitude effects due to convection electric fields and particle precipitation by *Schunk et al.* [1975, 1976]. A simplified ion energy equation was also added, which was based on the assumption that local heating and cooling processes dominate (valid below 500 km). Flux tubes of plasma were followed as they moved in response to the convection electric fields. The addition of plasma convection and particle precipitation models is described by *Sojka et al.* [1981a, 1981b]. *Schunk and Sojka* [1982] extended the ionospheric model to include ion thermal conduction and diffusion thermal heat flow. Also, the electron energy equation was included by *Schunk et al.* [1986], and consequently, the electron temperature is now rigorously calculated at all altitudes. The theoretical development of the TDIM is described by *Schunk* [1988], while comparisons with observations are discussed by *Sojka* [1989].

[7] Plasma transport plays a critical role in the polar *F* region, so a model of the convection electric field is needed; throughout this study we use slightly modified convection patterns from *Heppner and Maynard* [1987]. These patterns allow us to use a variety of orientations of the Interplanetary Magnetic Field (IMF) and different levels of the geomagnetic activity, represented by the planetary K index (K_p). For those TDIM simulations in which the auroral precipitation has not been set to zero, the K_p-dependent auroral electron precipitation model of *Hardy et al.* [1987] is used. As already mentioned the Hardy oval does not include energy fluxes associated with the very soft precipitation that can be present in the cusp. For those simulations in which the solar EUV has not been set to zero, we use solar medium conditions, with $F_{10.7} = 150$. In all cases the MSIS thermospheric model [*Hedin*, 1987] is used. The TDIM has an upper boundary at 800 km at which topside fluxes and heat fluxes are used to represent the upward continuation of the flux tubes. These boundary conditions vary over the day, night, and auroral region by scaling with solar zenith angle and auroral energy fluxes.

3. Model Results

[8] When studying observations of plasma in the *F* region, it is not possible to determine how much of the ionization source was auroral precipitation, and how much was solar EUV radiation; thus it is difficult to estimate how much of the total polar cap plasma was created by each of these processes. In this study we take advantage of using an ionospheric model, with which we can separate completely the effect of these two sources, by running the model with either zero auroral input, or with zero solar EUV input. It is in no way intended that either of these must represent a physically realizable situation (though it is true that a winter polar cap at the appropriate UT can become devoid of solar EUV, and that possibly extremely quiet geomagnetic activity corresponds to almost no auroral precipitation). In this study contrasting a no-solar-EUV simulation with a no-aurora simulation allows an examination of the relative contributions of the two sources. It is noteworthy that these separate simulations produce *F* region densities, which when added together almost exactly reproduce the full model simulation density.

[9] The desire to make this comparison comes from the fact that the degree of solar illumination and solar EUV intensity is always known for any season and UT, while the

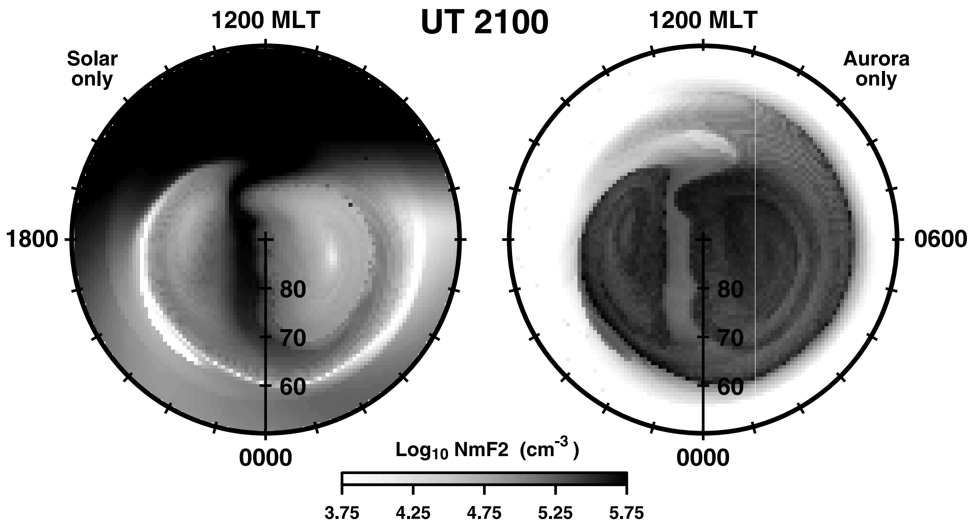

Figure 1. Two dial plot snapshots of simulated N_mF_2 over the Northern Hemisphere polar cap at 2100 UT in winter: the model was run (left) with no auroral input and (right) with no solar EUV input. The electron density is gray scaled as a $\log_{10}$ value over 2 orders of magnitude. A magnetic latitude and magnetic local time coordinate system is used.

average auroral precipitation is principally independent of season and UT with a variability that is almost stochastic. From a predictive capability perspective, one component is predictable while the other is only known in a statistical sense and hence it is important to determine if the latter plays a controlling role as a plasma source.

3.1. Solar and Auroral Production: UT

[10] In Figures 1 and 2 we show results of TDIM solar-only and aurora-only model runs. These runs are based on conditions of moderate geomagnetic activity, with the IMF B_y slightly negative and B_z southward, on a day near the winter solstice in the Northern Hemisphere. N_mF_2 is plotted as a "snapshot", i.e., a picture of the F region density peak over the polar cap at one instant of time, in particular, 2100 UT in Figure 1 and 0900 UT in Figure 2. These two times, 2100 and 0900 UT, are roughly the times of maximum and minimum TOI presence in the winter Northern Hemisphere, but note that these are not the times when the solar terminator lies furthest poleward or equatorward; this is because the plasma takes several hours to be convected through the polar cap. Figures 1 (left) and 2 (left) show a solar-only run, in which the solar EUV radiation is allowed in the model to have its full ionization effect, but the auroral precipitation has been shut off entirely. Figures 1 (right) and 2 (right) show the corresponding aurora-only model runs, with the Hardy et al. auroral model for $K_p = 3$, but with the solar EUV radiation artificially set to 0. We again mention that this condition of zero sunlight is not intended to represent any physically real situation, such as an eclipse,

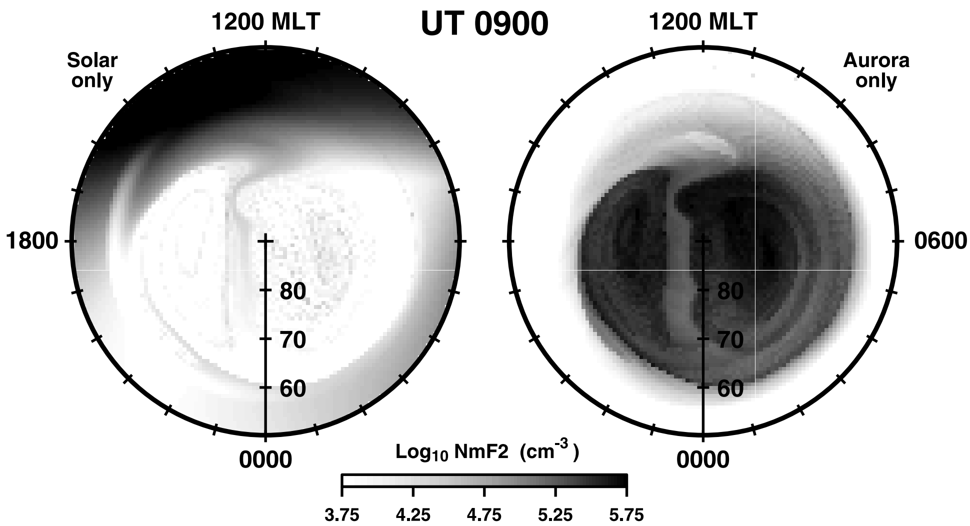

Figure 2. Two dial plot snapshots of simulated N_mF_2 over the Northern Hemisphere polar cap at 0900 UT in winter: the model was run (left) with no auroral input and (right) with no solar EUV input. The format is the same as that used in Figure 1.

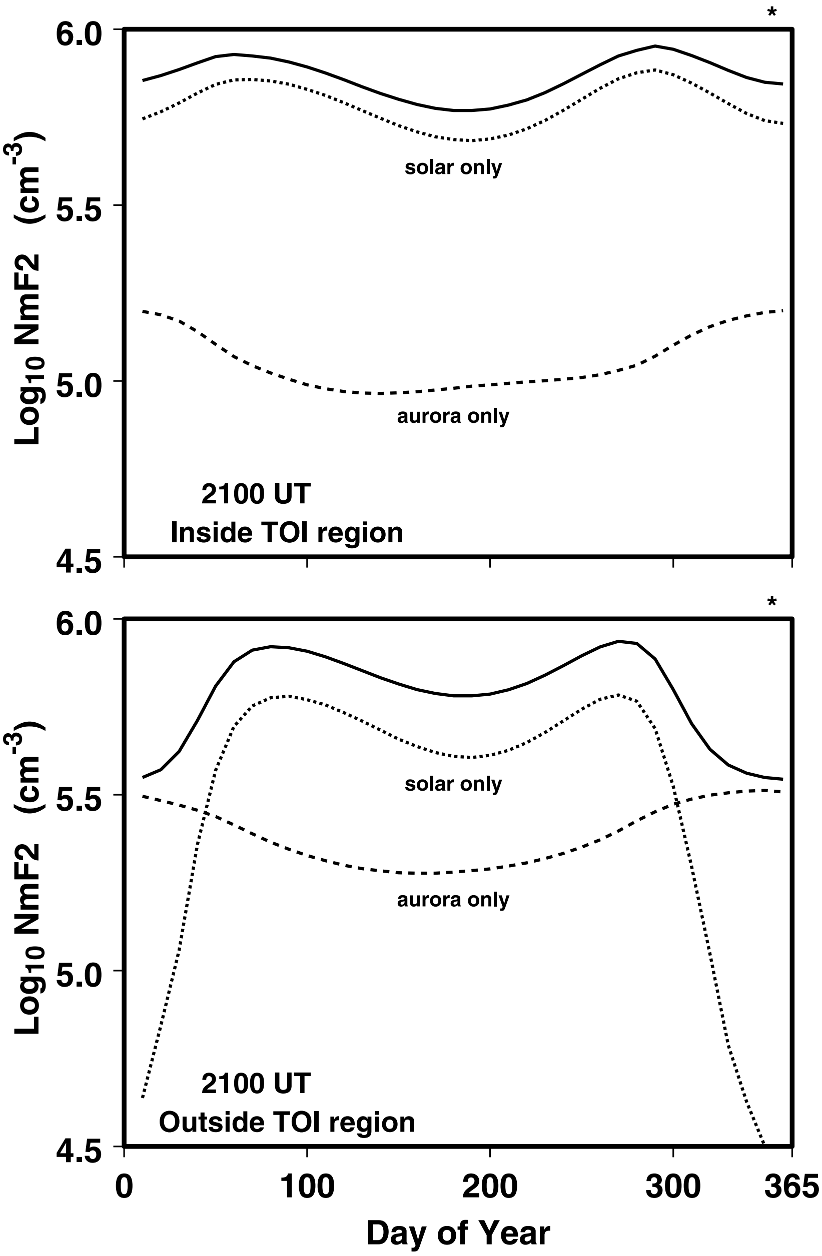

Figure 3. The seasonal dependence of N_mF_2 (top) inside the TOI region and (bottom) outside the TOI region at 2100 UT. The inside location is at magnetic latitude 85.7°N, 1900 MLT, and the outside location is at magnetic latitude 77.36°N, 0555 MLT. Three TDIM simulations are contrasted in each panel; the solid line is the normal TDIM, the dotted line is the solar-only case, and the dashed line is the aurora-only case. The asterisk identifies the winter day corresponding to Figure 1.

but is instead just a means of weighing the relative effects of the solar and auroral ionization in the F region.

[11] Figure 1 (left) shows the TOI in which high density plasma, created by solar EUV radiation on the dayside, has been convected through the cusp region and into the polar cap. Since this model run was done without auroral contribution, this is in effect a "pure" TOI. As it is a solar-produced feature, it must be expected to have a strong UT dependence, and indeed Figure 2 (left), at the UT twelve hours later, shows that the TOI has practically disappeared.

[12] Figures 1 (right) and 2 (right) show the results of aurora-only runs; as the solar contribution is removed, the UT dependence has virtually disappeared. (Any lingering UT effect is due to the neutral atmosphere model [*Hedin*, 1987] used by our ionospheric code. This neutral atmosphere model does not "know" that the sunlight has been removed.) These aurora-only runs show an interesting "negative TOI," that is, plasma depletion where the TOI enhancement would have been. This is due to low density plasma from equatorward of the auoral oval being convected into that region. This feature does also show up in normal model runs at those times when a TOI does not exist, such as 0900 UT in winter.

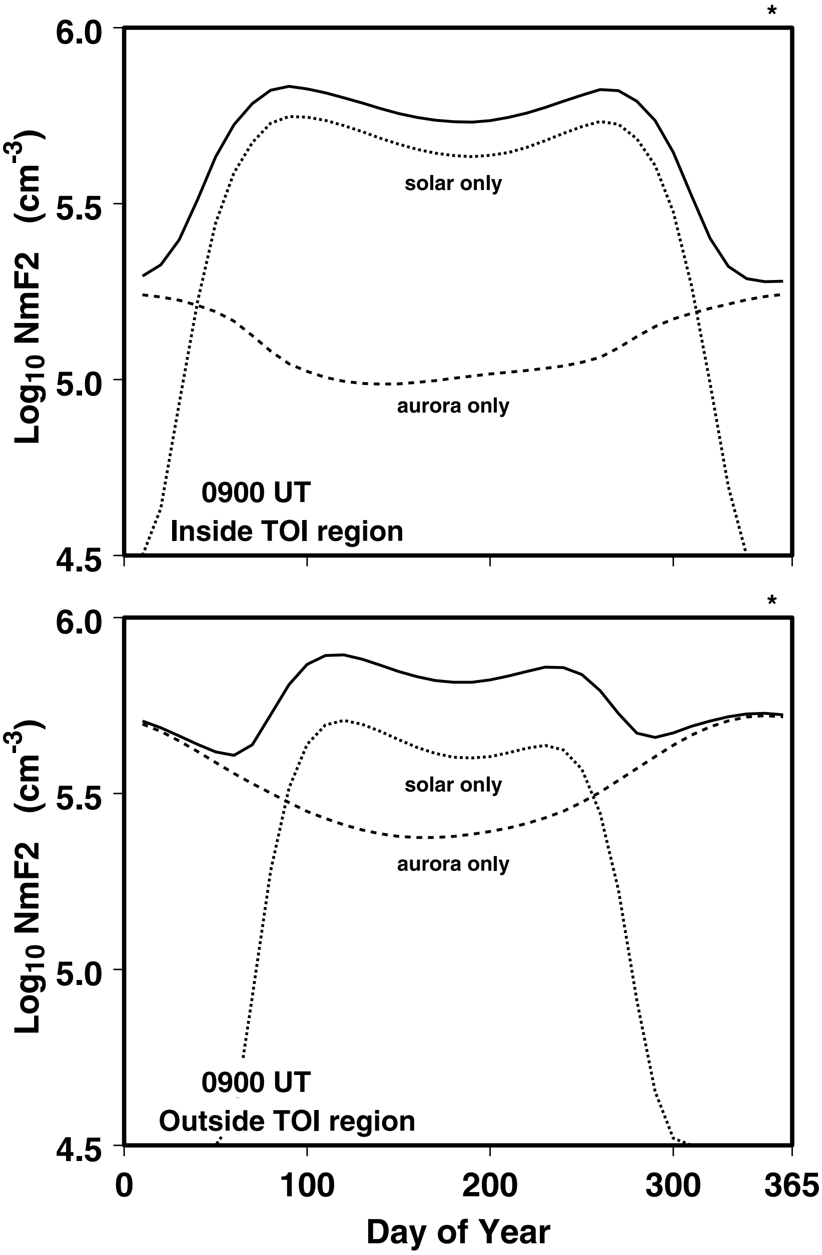

Figure 4. The seasonal dependence of N_mF_2 (bottom) inside the TOI region and (top) outside the TOI region at 0900 UT. The format is the same as that of Figure 3. The asterisk identifies the winter day corresponding to Figure 2.

[13] Figures 1 and 2 reveal that the winter TOI has a strong UT modulation, while the aurorally produced background densities show little or no UT modulation. It is true that Figures 1 (left) and 2 (left) do show that there is also a background level, with a UT dependence, associated with solar EUV production. This level, at least poleward of 60°, is sufficiently lower than that of the aurorally produced background that we feel justified in saying that the total background level does not show a significant UT variation. The convection of sunlit plasma into the polar cap produces densities up to about 6×10^5 cm^{-3} while the auroral production and convection results in densities as high as 4×10^5 cm^{-3} in locations adjacent to the TOI. Note that this comparison is for moderate geomagnetic activity, K_p = 3; changing K_p would result in both auroral precipitation and convection changing.

3.2. Solar and Auroral Production: Seasonal

[14] The winter polar ionosphere has a well defined difference between the source for the TOI and the background plasma. However, as the seasons change through equinox to summer the solar contribution to the background density increases raising the background to the point that the TOI becomes masked. When during the year does this transition occur?

[15] Figure 3 shows how the simulated N_mF_2 at 2100 UT varies with season, (Figure 3 (top)), and at a location outside the TOI (Figure 3 (bottom)). Each panel shows

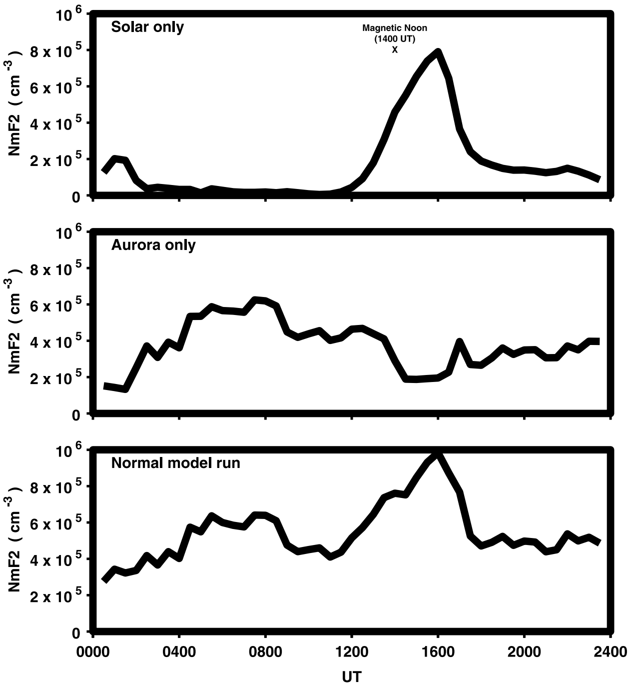

Figure 5. Diurnal variation of the TDIM N_mF_2 at a fixed location near Sondre Stromfjord (70°N, 310°E) for three simulations: (top) solar only, (middle) aurora only, and (bottom) normal TDIM for the same geomagnetic conditions used for Figures 1 and 2.

the normal TDIM simulation (solid curve), the no-aurora simulation (dotted line), and the no-sunlight simulation (dashed line). The top panel shows that at 2100 UT the TOI is always present and relatively insensitive to season. In contrast, the point outside the TOI, representing the background, is influenced by both solar EUV and the aurora during the day number periods 0 to 50 and 300 to 365. During equinox and northern summer, sunlight is the dominant process in generating the background density at this UT. During most of the equinox and northern summer period the TOI density relative to the background density is only a few tens of percent in comparison to the winter period where it almost reaches a factor of three larger than the aurorally produced background.

[16] At 0900 UT, when no TOI is seen in Figure 2, the situation is different. Figure 4 shows again the modeled N_mF_2 at two locations with their corresponding seasonal dependencies. In winter, days prior to day 30 and after day 310, the density in the TOI region is only about 2×10^5 cm^{-3} (Figure 4 (top)), the TOI region it is over 4×10^5 cm^{-3} (Figure 4 (bottom)). Hence the negative TOI can almost have as large a density ratio (inverted) as the real TOI at 2100 UT. Like the strong TOI ratio found only in northern winter at 2100 UT the strong negative TOI is also restricted to northern winter. Throughout the rest of the year sunlight dominates and reduces the negative TOI to only a few percent relative to the background.

3.3. Solar and Auroral Production: Ground Station

[17] In the two previous subsections the TDIM results were presented as polar cap snapshots and as seasonal variations at specific UTs and locations. Such an observational data set would be difficult to obtain. A more realizable format for the modeling presentation is to simulate what a ground station would observe in a day. Figure 5 shows the result of such a simulation sequence for Sondre Stromfjord (67°N, 310°E) for the conditions presented in Figures 1 and 2; these conditions are winter, moderate activity and a southward IMF with B_y being negative. The three panels show the no-aurora simulation (Figure 5 (top)), no Sun (Figure 5 (middle)), and the normal TDIM simulation (Figure 5 (bottom)). By inspection of the no-aurora panel (Figure 5 (top)), the time when Sondre Stromfjord crosses the TOI is evident, i.e., 1400–1600 UT. This is also reflected in a reduction of the auroral contribution (Figure 5 (middle)). What would be seen at this site, i.e., the normal TDIM run, is shown in the bottom panel and in this case a well defined TOI is still observed, a factor of two above background.

[18] Not all sites in the polar cap are as well located to observe the TOI. Figure 6 repeats the Figure 5 presentation but for the NyAlesund location at 79°N 12°E. This station, like Sondre Stromfjord, is at a cusp/polar cap location. However NyAlesund, unlike Sondre Stromfjord, is located where the cusp region is in darkness in the middle of winter. This is expected to have an impact on this station's ability to see the TOI. Figure 6 (top) shows this impact. NyAlesund does not see a TOI at magnetic noon because of the dark conditions in winter. Rather 12 hours later, around magnetic midnight (1900 MLT), it sees a TOI after it has been transported across the polar cap. Around magnetic noon the aurorally produced ionization (Figure 6 (middle)) shows a dip because the *Hardy et al.* [1987] precipitation model does not contain a soft cusp precipitation source. At this longitude the result is a reduction in N_mF_2 at magnetic

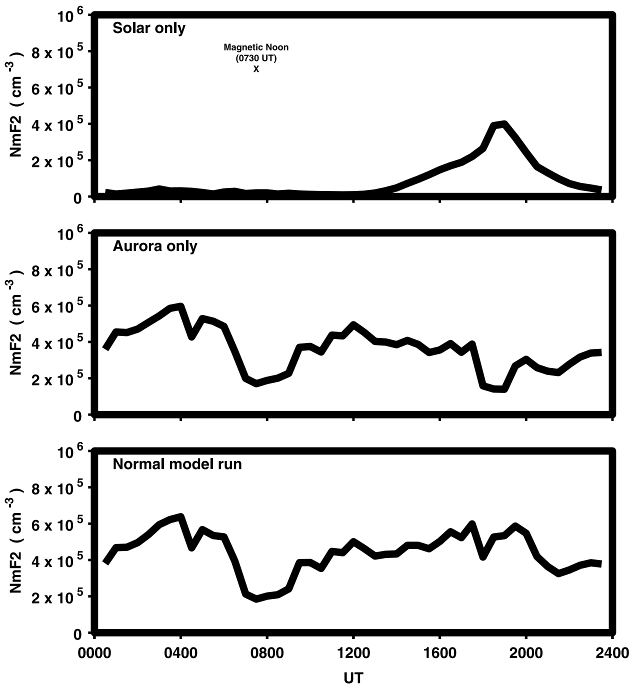

Figure 6. Same as Figure 5 except the fixed location is at NyAlesund (79°N, 12°E).

noon (see Figure 6 (bottom)). Note that the simulation carried out here has been for only one set of geophysical conditions; the TOI visibility at any given station is expected to change if K_p or the IMF orientation changes. In fact, for another orientation of the IMF, perhaps NyA-lesund might see the noon TOI, while Sondre Stromfjord would not.

4. Discussion

[19] The previous section highlights the difficulty of comparing observations at individual polar cap stations with models. Even though Figures 5 and 6 show simulations based upon extremely steady conditions for 24 hours, i.e., fixed IMF, K_p, A_p, $F_{10.7}$, etc., still the two stations are predicted to observe entirely different UT variations. Figures 5 (bottom) and 6 (bottom) show almost no common features. Arguably they both are predicted to see an average N_mF_2 of about 5×10^5 cm^{-3}, with only Sondre Stromfjord being predicted to reach 1×10^6 cm^{-3}. It is of interest to determine if this 5×10^5 cm^{-3} background in itself can usefully be studied. Would such a background level be meaningfully compared to average auroral conditions or specific seasons when solar effects are negligible? The background density in winter, as shown in Figures 4, 5, and 6, is largely dependent upon auroral precipitation. Does variability in auroral precipitation smooth out sufficiently through longer F region time constants that the background density is a reasonable proxy of integrated auroral conditions?

[20] *Fuller-Rowell et al.* [1991] carried out three simulations using the coupled UCL/Sheffield thermosphere/ionosphere model for December solstice $F_{10.7} = 185$ conditions. Their three simulations showed the relative contributions of solar EUV, solar EUV + convection, to solar EUV + convection + auroral precipitation drivers on the F region at 1800 UT. Although their results are only at one UT, the relative contributions can be qualitatively seen to be consistent with our study. Specifically with solar EUV + convection the polar cap background is $\leq 1.0 \times 10^5$ cm^{-3}, whereas with the auroral oval included the density increases by about 3×10^5 cm^{-3}. Although no high resolution TOI structure is modeled, the highest polar cap densities do reach 8×10^5 cm^{-3}. These qualitative dynamic ranges agree well with this study's results. The *Fuller-Rowell et al.* [1991] study clearly demonstrates the fact that plasma convection is the dominant mechanism for distributing F region plasma in the polar regions. This fact was the starting place for our study and hence only the solar EUV and auroral precipitation were regarded as adjustable parameters to be turned on/off.

[21] In Figures 5 and 6 only two sites have been compared and only for winter conditions. If the IMF B_y orientation were changed, the location of the TOI in the polar cap would change and the sites would see yet other patterns. Moreover, if realistic dynamics were introduced, polar cap patches would be the rule, rather than a stable TOI as shown in Figure 1. The creation of patches, in turn, would further complicate the Figures 5 and 6 morphologies. However, TOI simulations may predict the dynamic range of densities to be expected for a given station for a range of solar, IMF, and geomagnetic conditions. The situation is further complicated by the role of soft cusp precipitation on the F region density. *Millward et al.* [1999] carried out a one flux tube test simulation of the effects of soft electron and ion cusp precipitation. Their simulation conditions were the cusp at 0917 to 0930 UT with $F_{10.7}$ index of 165. Several different Maxwellian distributions were simulated ranging from 50 to 900 eV. In each case energy fluxes close to the maximum based upon DMSP satellite observations were used. For the case of the very soft 50 eV electron precipitation they created F region enhancement of 6.0×10^5 cm^{-3}. Comparing these maximum density enhancements with those found in Figures 5 and 6 indicates they are significant. In Figure 5 the TOI contribution from solar EUV at solar medium conditions of $F_{10.7} = 150$ is 8×10^5 cm^{-3}. The background auroral contributions from the *Hardy et al.* [1987] oval ranges from 2 to 6×10^5 cm^{-3}. Hence the soft precipitation component of up to 6×10^5 cm^{-3} is on the same order as the other sources. For the Figure 6 case in which the TOI at magnetic noon is negligible and the background Hardy et al. auroral contribution has a depletion at magnetic noon (cusp) the soft precipitation would potentially fill in the cusp depletion. Unfortunately there does not exist a suitable soft precipitation model (specifically <500 eV). It is unclear how frequently the cusp is dominated by 50 eV electrons close to the maximum observed energy flux as modeled by *Millward et al.* [1999]. There is a need for such a model, not just in the cusp, but over the whole high latitude area especially during northward IMF conditions when soft auroral precipitation is present throughout the polar regions.

5. Conclusion

[22] In this study we have used a physical model of the ionosphere (TDIM) to assess the relative solar and auroral contributions to polar cap plasma. Bearing in mind the limited conditions of the study, we draw the following conclusions.

1. In winter the solar-generated TOI exists between about 1700–2400 UT. During some other UTs there may be a "negative" TOI, a density depletion tongue.
2. In winter, auroral production is responsible for the largest part of the background density; it dominates the polar cap density during those times when the TOI is absent.
3. During equinox and summer most polar cap plasma is solar produced with the auroral contribution being relatively small.
4. Observations made at specific polar cap locations are related in complex ways to the actual ionospheric drivers. A large scale feature such as the TOI may be observable at one location, while being masked by background plasma at another. The TOI (or patch) visibility at any given location will be determined by the current conditions and recent histories of geomagnetic activity and IMF orientation.

[23] This study highlights the need for two follow on studies. The first is to use a large observational data base to attempt a model validation of the winter F region background plasma density. Such a study has begun using DE-2 data. A second modeling study to predict how different geographic locations may or may not be able to see TOIs or patches needs to be undertaken to establish how observations distributed over the polar regions can be combined to

specify the ionospheric drivers and the distribution of large scale plasma structures.

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